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Testing the limitations of buffer zones and Urban atlas population data in urban green space provision analyses through the case study of Szeged, Hungary

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A R T I C L E I N F O

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A B S T R A C T

A liveable city requires urban green spaces (UGS) in many locations, since such spaces have a direct impact on the quality of life and overall well-being of city dwellers. UGS provision analyses therefore have been attracting a number of researchers, practitioners and decision makers for recent years using various methodologies. In this study, we conduct reference UGS provision analysis using accurate input data, calculating the population with access to a UGS within fifteen minutes of walking, with a one-minute resolution. These results are employed as reference for quantifying the spatial accuracy of buffer zone-based isochrone maps and the overall (thematic and scale) accuracy of the European Environmental Agency's Urban Atlas population database in UGS provision estimation. The estimated differences between the Urban Atlas and the reference data in UGS provision assessment are 11.8 % (6861 people) within 10 min and 11.8 % (7050 people) within 15 min of walking. The difference between estimates from buffer zone-based isochrone maps and the reference is 2.1 % (1479 people) within 10 min and 0.1 % (77 people) within 15 min of walking. Further statistical analyses reveal that the spatial accuracy (correlation coefficient with reference = 0.7878) of the buffer zone-based map's impact on the result of UGS provision estimation is more than the overall accuracy of the Urban Atlas' population database (correlation coefficient with reference = 0.9798). These results may potentially enhance the knowledge about the limitations, usefulness and reliability of the buffer zone-based isochrone maps and the European-scale land cover and population dataset in spatial analyses of UGS provision. The results of this study can be used for improving the accuracy of buffer zone- and Urban Atlas-based UGS provision mapping estimates at local and regional scales.

1. Introduction

Through their social and recreational benefits, as well as ecosystem functions, urban parks, urban forests and other pockets of informal green spaces (Rupprecht et al., 2015; Stessens et al., 2017) are vital for the liveability of cities including the well-being of residents (Neuvonen et al., 2007; James et al., 2009; Schipperijn et al., 2010; Kovacs-Györi et al., 2018). Considering their importance, the assessment and quantification of urban green spaces (UGS) as well as the UGS provision or UGS access has attracted significant interest from researchers, practitioners and city administrators (Zepp et al., 2020). Several studies focus on the spatial characteristics (through e.g.: accessibility mapping) of green space provision (Lee and Hong, 2013; La Rosa, 2014; Yuan, 2016; Kolcsár and Szilassi, 2018), while others emphasize the assessment of attractiveness and functionality (Chiesura, 2004; Kothencz et al., 2017; Roberts, 2017; Roberts et al., 2019; Szilassi et al., 2020). There are also studies involving a holistic approach concerning this issue (Giles-Corti et al., 2005; Hillsdon et al., 2006; Kovacs-Györi et al., 2018). The study of the UGS provision and/or UGS access assessments is important from various aspects. Firstly, adequate provision of UGS has direct influence on the welfare of city dwellers (Schipperijn et al., 2013; Koppen et al., 2014; Boros et al., 2016; Kolcsár and Szilassi, 2018; Kovacs-Györi et al., 2018; Kowarik, 2018; Zepp et al., 2020). Secondly, mapping UGS access is also valuable for urban planning, because it has the potential to help with the identification of districts where the number of UGS is scarce. Studies suggests that the presence of a green space within 10–15 min walking from residents' home is an important characteristic of liveable cities which is a pivotal information for urban planners (Stanners and

Abbreviations: UGS, urban green spaces; LULC, land use and land cover; HMI, Hungarian Ministry of Interior; POI, point of interest.

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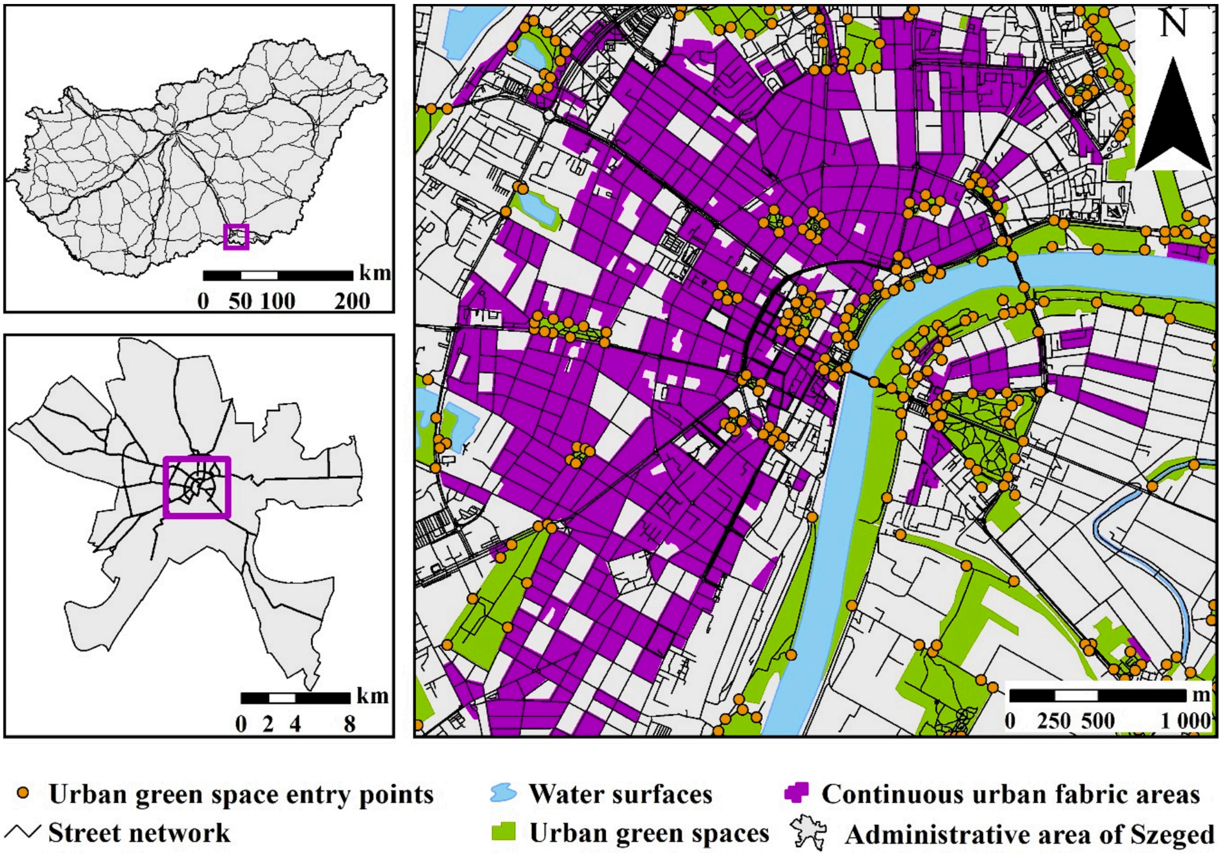

Fig. 1. The continuous urban fabric areas of the study area (Szeged) with the Urban Green Spaces and their designated entry points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Bourdeau, 1995; Pafi et al., 2016; Stessens et al., 2017; Kovacs-Györi et al., 2018; Le Texier et al., 2018; Poleman, 2018). These scientific results help urban planners select the location of new green spaces (e.g.: through tree planting or grassing in vacant lots and streets) thus helping UGS provision to be improved (Van Herzele and Wiedemann, 2003; Comber et al., 2008; Ekkel and de Vries, 2017; Fan et al., 2017). Besides the city-scale studies of UGS provision, regional-scale studies also exist. Through these analyses, the urban green area per capita is calculated, which is an important indicator of UGS provision and helps identifying cities requiring UGS provision improvement (Badiu et al., 2016; Russo and Cirella, 2018; Lin et al., 2019).

While there is no uniform definition for UGS provision and UGS access in the scientific literature, most studies assess the distance and/or the quality of the UGS, and in many cases, study the affected population that can benefit from these UGS as well. Biernacka and Kronenberg (2019) for instance, proposed three main levels of 'UGS provision': availability, accessibility and attractiveness. In their interpretation, availability is the existence of an UGS within a bee line distance. It is usually measured with Euclidean distances and green space coverage within buffer zones (Kronenberg, 2015; Kabisch et al., 2016; Biernacka and Kronenberg, 2019; Biernacka et al., 2020). Compared to availability, accessibility is a more complex characteristic of UGS provision. Representing the physical and psychological possibilities of UGS usage, it considers the various barriers (e.g. fences or buildings) along the road network (Wright Wendel et al., 2012; Park, 2017; Biernacka and Kronenberg, 2019; Biernacka et al., 2020). Conversely, attractiveness essentially involves the quality of UGS, describing their desirability to potential visitors. Composite indicators (e.g. the ParkIndex) often prove to be the most adequate tool for the quantification of this UGS provision level (Stessens et al., 2017; Biernacka and Kronenberg, 2019; Biernacka et al., 2020). Le Texier et al. (2018) on the other hand defined four levels of 'UGS provision and access': availability, fragmentation, public-private ownership, and accessibility. This interpretation of UGS availability is limited to the measurement of the area of UGS compared to total area of a city or sub-part of a city, while the measurement of distance between UGS and its neighbourhood falls exclusively within the domain of accessibility. Other studies defined levels of 'green space access' as follows: virtual access, viewing, utilising and being in green space, active hands-on engagement and ownership and/or management (Weldon et al., 2007; Edwards et al., 2009). Another important aspect of UGS provision estimation is determining the fraction of a population capable of reaching green spaces within a given walking time (Zepp et al., 2020). Many studies combine availability or accessibility analysis and population data to estimate the number of residents that can reach a destination in predetermined time intervals (Bok and Kwon, 2016; Poleman, 2018; Zepp et al., 2020).

Studies that deal with UGS access often utilize street network-based service areas as it is considered one of the most precise methods of quantifying the real distances between points within an urban area (Koppen et al., 2014; Bok and Kwon, 2016; Pafi et al., 2016; Yuan, 2016; Gu et al., 2017; Le Texier et al., 2018; Quatrini et al., 2019; Zhang and Tan, 2019; Wen et al., 2020). Other studies, however, use buffer zones for delineating 'walkable' catchment areas of UGS (Oh and Jeong, 2007; Braquinho et al., 2015; Bahrini et al., 2017; Koprowska et al., 2018). The use of service areas (created through network analyses) is often a more preferred choice compared to buffer zones, because the latter approach frequently produces underestimated travel times, or alternatively, overestimates walkable distances (Shahid et al., 2009; Le Texier et al., 2018; Mora-Garcia et al., 2018). The combined utilization of buffer zones and networks is also not unprecedented in the scientific literature (Gupta et al., 2016). The usage of such or methodologies is not exclusive to UGS, there are also numerous studies on accessibility in health care

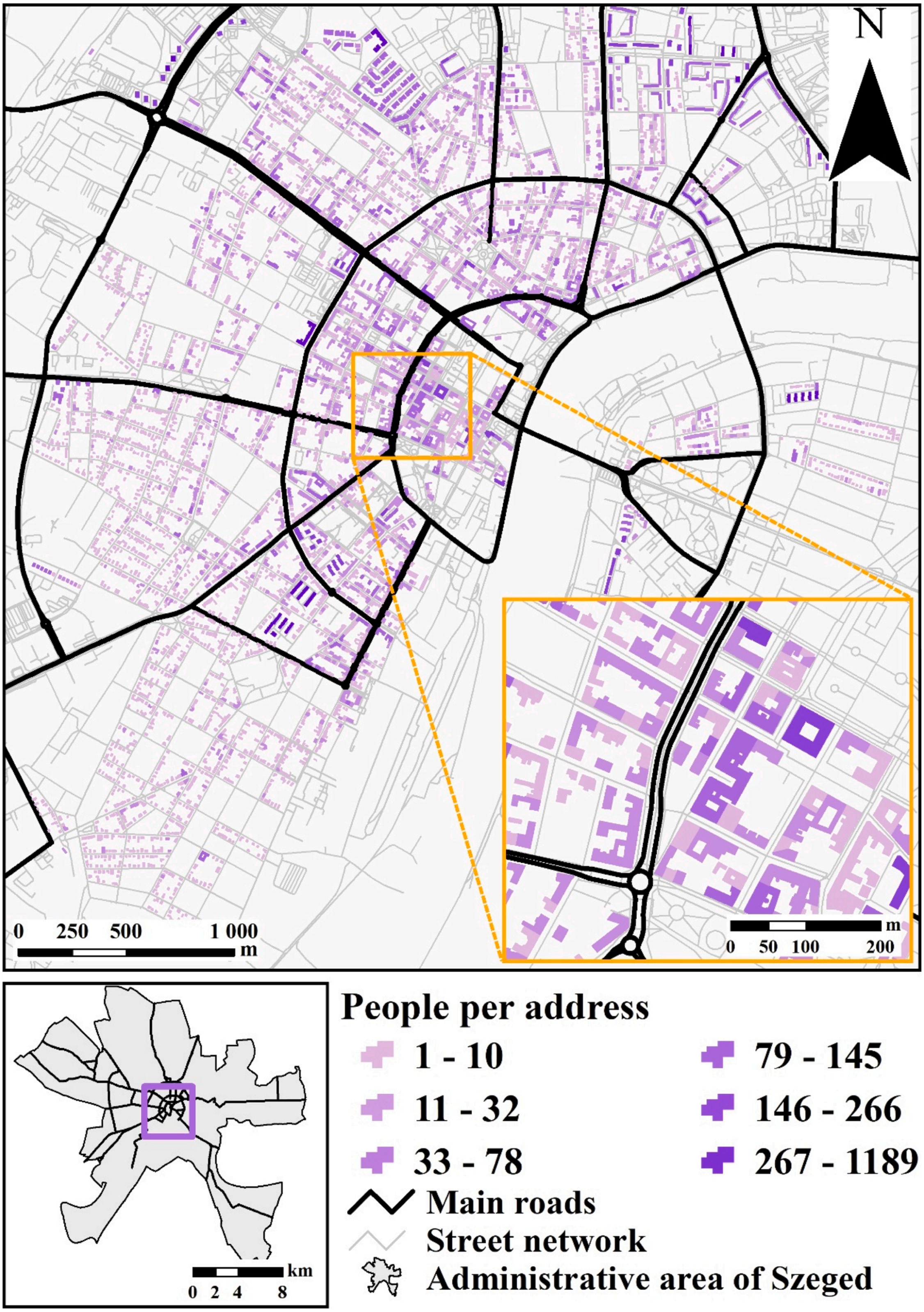

Fig. 2. Address-level population data of the Hungarian Ministry of Interior (HMI) assigned to the OpenStreetMap building polygons.

and other sectors (Hare and Barcus, 2007; Kwan and Weber, 2008; McGrail and Humphreys, 2009).

The population living within a defined walking duration from a UGS can be assessed using isochrone maps and population data, but the output accuracy depends on the quality of the input datasets. Therefore, the limitations of the freely accessible data for these inputs in UGS provision mapping remains unclear. In this study, we carry out UGS provision assessment of the continuous urban fabric of Szeged (European Commission, 2016) with the help of the most detailed isochrone maps and population data available. The results are used as reference for assessing the reliability of buffer zone (Euclidean distance)-based isochrone maps and Urban Atlas population data in estimating UGS provision. In addition, spatial, thematic and scale accuracy analyses are conducted directly on the input data that were used in the UGS provision modelling. The objective of this study is to provide quantitative information about the usability of buffer zone-based isochrone maps and population data from the Urban Atlas in UGS provision assessment. In order to obtain this information, a simple method with highly detailed reference input data (service area-based isochrone map address level population data) was used to make estimates about the population that can reach the closest UGS by walk in different travel durations. The same estimates were made by using buffer zones and/or the Urban Atlas populations. The differences of these estimates compared to the reference were the base of various spatial and statistical analyses to quantify the usability of these widely accessible data sources.

The questions examined are the following:

- What is the spatial accuracy of the buffer zone-based isochrone mapping compared to the service area method?
- How reliable is the population database of Urban Atlas dataset compared with high resolution address-level population data?
- What are the limitations of the buffer zone-based isochrone mapping methods and the population database of the Urban Atlas in the urban green space provision analysis?

Answering these questions could provide the scientific community with further knowledge about the usefulness of the buffer zone-based isochrone maps as well as the Urban Atlas land cover and population dataset in the spatial analysis of UGS provision. Consequently, enabling more optimized input data selections in future similar studies.

2. Materials and methods

2.1. Study area

This study was conducted in Szeged, the largest city in the Southern Great Plain region in Hungary (Fig. 1). The isochrone mapping was based on UGS from the entire city, whereas the UGS provision estimates are limited to urban areas with 80 % or higher covered by buildings. These areas are classified in the Urban Atlas as ‘continuous urban fabric’ and are tagged using code 11,000 (see Fig. A1). Due to the high building coverage, continuous urban fabric involve the least local green spaces such as private gardens or low informal green space pockets (Rupprecht et al., 2015). Green space provision is therefore the most important issue in these continuous urban fabric areas within the city.

2.2. Datasets utilised

2.2.1. Urban atlas land cover database

For quantitative analyses of UGS provision, the most recent (2012) Urban Atlas data was utilised (Copernicus, 2020). Urban Atlas is a GIS database created by the European Environmental Agency, containing spatial and statistical data for 800 Functional Urban Areas of Europe such as LULC types, area and population data for different land cover patches. Due to free accessibility and high resolution, Urban Atlas is widely exploited by researchers (Barranco et al., 2014; Petrişor and Petrişor, 2015; Akay and Sertel, 2016; Pazúr et al., 2017; Pirowski and Timek, 2018; Poleman, 2018; Kovács et al., 2019; Kukulska-Kozieł et al., 2019; Quatrini et al., 2019; Zepp et al., 2020). The five main LULC classes in the Atlas are: Class 1 - artificial surfaces, Class 2 - agricultural areas, Class 3 - natural and semi-natural areas, Class 4 - wetlands and Class 5 - water (European Commission, 2016). These classes are further

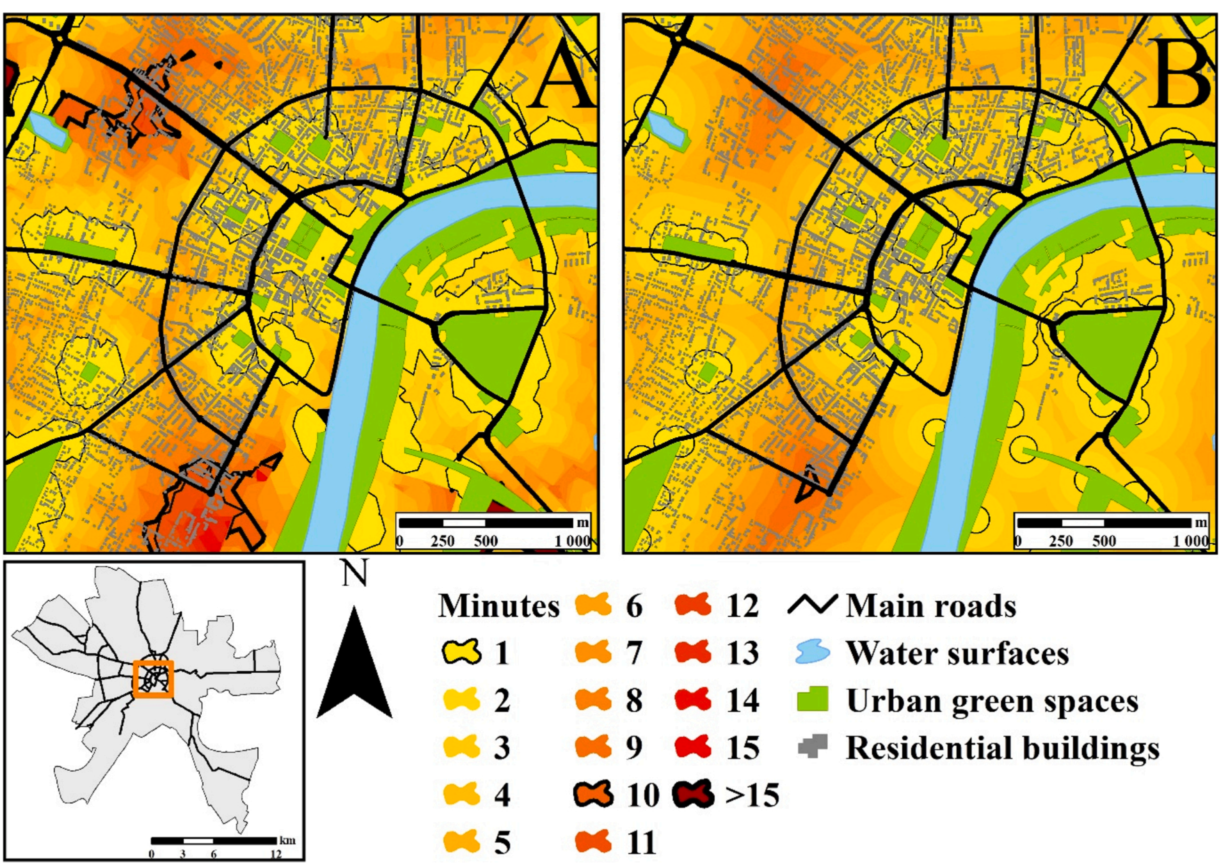

Fig. 3. Estimated walking distances in minutes according to the (A) service area and (B) buffer zone-based isochrone maps highlighting areas with poor overall UGS accessibility in the continuous urban fabric.

divided into four subcategories (see Fig. A1), with a minimum mapping unit of 0.25 ha for Class 1 and 1 ha for Classes 2–5 (European Commission, 2016). In specific cases, polygon sizes below the minimum mapping unit can also be found in Urban Atlas. Polygons of multiple LULC types were selected and used for the isochrone mapping and the UGS provision assessment. The LULC category of the ‘continuous urban fabric’ area was used as the study area in the UGS provision estimation. Since there is no universal definition for UGS (Rupprecht et al., 2015; Zepp et al., 2020), selecting LULC types in the Urban Atlas representing UGS of Szeged required an arbitrary approach. The green urban areas, forests, herbaceous vegetation and wetland categories were selected as the destination polygons of the isochrone mapping. Among the four selected LULC types, green urban areas and forests are dominant in Szeged. with marginal The presence of herbaceous vegetation and wetlands in the city is marginal and is mainly limited to the outskirts. The water surface polygons were only used to visually highlight rivers and lakes as potential walking barriers in Szeged (see Fig. A1).

2.2.2. Databases for estimating population

We obtained a detailed and very accurate building-scale dataset from the Hungarian Ministry of Interior (HMI) containing the population distribution of Szeged from 01.01.2019. The population data within the continuous urban fabric areas was assigned to OpenStreetMap’s building polygons, thus creating a geo-tagged population dataset, with missing or obsolete building polygons manually redrawn (Fig. 2). Since this database involves the highest accuracy we could obtain, it served as a reference for input data in the assessments.

The Urban Atlas also includes population data for each LULC polygon in its attributes table (Copernicus, 2020). These data are from the best available census data of each European country (Batista e Silva et al., 2013; Batista e Silva and Poleman, 2016). In the case of Szeged, this population data is derived from the 2011 census. The population database was compared to the reference population dataset of HMI in the accuracy assessments (Fig. A1).

The difference between the Urban Atlas population database and the reference population data of HMI is attributed to scale and the residential data source (2011 census for Urban Atlas and 2019 address register for HMI population data). Therefore, differences in the reference results produced by using the Urban Atlas data are described in the study as overall (thematic and scale) accuracy.

2.3. GIS methods for isochrone mapping

As the first step of isochrone mapping, polygons representing UGS were selected from the Urban Atlas dataset (see Fig. A1). Secondly, the detailed street network of the OpenStreetMap was overlaid on the layer, and where the roads intersected the polygons, UGS entry points were generated. These points served as travel destinations in the isochrone mapping (Fig. 1). In order to estimate UGS access, two types of isochrone maps were created; one was service areas-based and one based on the buffer zone-based isochrone mapping methodology.

The service areas were created in ArcGIS Pro Online with the help of the Network Analyst’s Service Area tool. This tool delineates areas on a map that are reachable from specific points or these points can be reached from by walking (with 5 km/h walking speed) within a predefined time. The tool also enables distance calculation on a built-in road network (provided by HERE Technologies, a partner company of ESRI), so that the shapes and sizes of the generated service area polygons are dependent on the properties of the area’s road network. The results layer of the Service Area tool comprised multiple overlapping polygons (15 polygons/UGS entry points). The one-minute service areas of each UGS entry point were merged, thereby delineating points in Szeged from where the nearest UGS was accessible by walking within a minute. Next, the two-minute service areas were also merged, and then added to the one-minute layer, showing all points in the city from where the closest green area was reachable by walking within two minutes. This process was repeated until all fifteen service area polygons were merged. The final isochrone map (Fig. 3) shows the time required to reach the nearest UGS entry point by walking from any area in Szeged. We selected 15 min as the maximum analysed walking time because previous studies suggest 10−15 min as the optimal walking time for UGS accessibility (Stanners and Bourdeau, 1995; Pafi et al., 2016; Kovacs-Györi et al., 2018; Le Texier et al., 2018; Poleman, 2018). This service area-based isochrone map was considered as the reference isochrone map because this method is considered to estimate pedestrian walking times to the UGS entry points most realistically (Gupta et al., 2016).

Table 1
Calculated buffer zone distances within specific walking times at 5 km/h walking speed.

Walking time (min)	Buffer distance (m)
1	83
2	167
3	250
4	333
5	417
6	500
7	583
8	667
9	750
10	833
11	917
12	1000
13	1083
14	1167
15	1250

Through the Euclidean distance-based mapping methodology, buffer zones were generated in ArcMAP and merged similar to the service area polygons. The zones distances were calculated by considering 5 km/h as the walking speed in the Network Analyst tool, thus making the two types of isochrone maps comparable (Table 1).

An advantage of the buffer zone map type is its relatively quick generation in any GIS software, with only basic user level knowledge required. They represent similar walking times, but differences in the creation methodology may cause the shapes, sizes and spatial positions to differ from those of the service area-based map. Therefore, differences from the reference (service area-based map) in the UGS provision estimations are defined in the study as spatial accuracy.

2.4. Direct spatial, thematic and scale accuracy estimations involving difference maps

2.4.1. Direct spatial accuracy estimation of the buffer zone-based mapping methodology

For isochrone maps, the shape layers of the service areas and the buffer zones were merged in ArcGIS, creating a new layer with multiple polygon fragments. Within each polygon fragment, the estimated walking time difference between the two isochrone maps were calculated by subtracting the values of the reference service area layer from values of the test buffer zone layer. Therefore, negative values imply underestimation and positive values mean overestimation of the walking distance by the buffer zone-based isochrone map. The values are obtained from the following equation:

$$t = t_{buff} - t_{ser}$$

where

t is the walking distance estimation difference between the buffer zone and service area-based isochrone maps within a polygon fragment (minutes),

t_{buff} is the estimated walking distance of the buffer zone-based isochrone map within a specific polygon fragment (minutes),

t_{ser} is the estimated walking distance of the service areas within a given polygon fragment (minutes).

To quantify the spatial accuracy of the buffer zone-based isochrone map, descriptive statistics (minimum, maximum, range, mean, average underestimation, average overestimation and standard deviation) were calculated from the *t* values. These statistics, however, can be biased by the difference in areas covered by individual polygon fragments. To eliminate disproportional representation of very small or considerably large polygon fragments, the weighted arithmetic mean was also calculated. These included separate calculations for the negative and positive values, to obtain the average underestimation and overestimation from the following expression.

$$\bar{t} = \frac{\sum_{i=1}^{n} w_i t_i}{\sum_{i=n}^{n} w_i}$$

where

$\bar{t}$ is the weighted arithmetic mean of the estimated walking time difference between the buffer zone and service area-based isochrone maps in each polygon fragment,

t is the walking distance estimation difference between the buffer zone and the service area-based isochrone maps within a specific polygon fragment (minutes),

w is the area of given polygon fragment (ha).

The weighted standard deviation was also calculated to eliminate the area-derived bias from the following expression:

$$sd_w = \sqrt{\frac{\sum_{i=1}^{n} w_i \left(t_i - \bar{t}\right)^2}{\frac{n-1}{n}\sum_{i=1}^{n} w_i}}$$

where

sd_W is the weighted standard deviation of the estimated walking time difference between the buffer zone and the service areas-based isochrone maps in each polygon fragment,

$\bar{t}$ is the weighted arithmetic mean of the estimated walking time difference between the buffer zone and the service area-based isochrone maps in each polygon fragment,

t is the walking distance estimation difference between the buffer zone and service area-based isochrone maps within a given polygon fragment (minutes),

w is the area of the given polygon fragment (ha).

2.4.2. *Overall (thematic and scale) accuracy estimation of the Urban Atlas population data involving difference maps*

Similar to the spatial accuracy test of the isochrone maps, a difference map of the two population databases was also created. Here, the building-scale population data of HMI assigned to the OpenStreetMap building polygons were aggregated on the polygons of Urban Atlas by location within the continuous urban fabric of Szeged. The estimated population difference was calculated for each polygon on the layer. As for the isochrone difference map, the reference population data of HMI was subtracted from the population data of the Urban Atlas, creating results with negative values indicating underestimation and positive values indicating overestimation. The calculation was based on the following equation:

$$p = p_{UA} - p_{HMI}$$

where

p is the estimated population difference between the population data from the Urban Atlas and that from the HMI within given Urban Atlas polygon (capita),

$p_{UA}$is the estimated population data from the Urban Atlas in each Urban Atlas polygon (capita),

p_{HMI} is the estimated HMI population data aggregated to the same Urban Atlas polygon (capita).

The overall accuracy quantification of the Urban Atlas population data was conducted by the same methodology involving descriptive statistics (minimum, maximum, range, mean, average underestimation, average overestimation and standard deviation). Weighted arithmetic means and weighted standard deviations were performed as for the walking distances to eliminate statistics bias from the Urban Atlas polygons sizes. The weighted arithmetic mean was calculated from the equation given as:

$$\bar{p} = \frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=n}^{n} w_i}$$

where

$\bar{p}$ is the weighted arithmetic mean of the estimated population difference between the Urban Atlas and the HMI data aggregated within the Urban Atlas polygons (capita),

p is the estimated population difference between the Urban Atlas and the HMI data in an Urban Atlas polygon (capita),

w is the area of an Urban Atlas polygon (ha).

The weighted standard deviation was derived from the following expression:

$$sd_w = \sqrt{\frac{\sum_{i=1}^{n} w_i \left(p_i - \bar{p}\right)^2}{\frac{n-1}{n}\sum_{i=1}^{n} w_i}}$$

where

sd_W is the weighted standard deviation of the estimated population difference between the Urban Atlas and the HMI data aggregated within the Urban Atlas polygons (capita),

$\bar{p}$ is the weighted arithmetic mean of the estimated population difference between the Urban Atlas and HMI data aggregated with the Urban Atlas polygons,

p is the estimated population difference between the Urban Atlas and HMI data for a given Urban Atlas polygon (capita),

w is the area of a polygon (ha).

Table 2
Urban green space provision estimation scenarios based on different input data combinations, Scenario 1 yielding the reference estimates while Scenarios 2-4 yielding the test estimates.

Isochrone map	Population data	
	Building-scale population data (HMI + OpenStreetMap)	Urban Atlas population data
Service area-based methodology	Scenario 1 Service area + HMI reference estimates	Scenario 3 Service area + Urban Atlas test estimates
Buffer zone-based methodology	Scenario 2 Buffer zone + HMI test estimates	Scenario 4 Buffer zone + Urban Atlas test estimates

2.5. *GIS method for estimating urban green space provision*

The definition and calculating methodologies of UGS provision vary in literature (Le Texier et al., 2018; Biernacka and Kronenberg, 2019; Biernacka et al., 2020). Walking distances as well as affected population are two of the more frequently used input data of UGS provision assessments (Biernacka et al., 2020; Zepp et al., 2020). In this study, we defined UGS provision as follows: the number of residents capable of reaching the UGS closest to their homes within a specified walking time. Therefore, polygons containing the building-scale HMI population data were grouped by their centroids within the walking time polygons of the service areas, thus creating Scenario 1 (Service area + HMI reference estimates) that was used as reference in further analyses. By utilising buffer zone and service area-base maps, the spatial aspect of UGS provision (availability and/or accessibility depending on the definition) was represented in the methodology. In favour of comparability we assumed that each UGS polygon derived from Urban Atlas is a public space and are equally attractive to the population. While further refinement of this data through manual override is possible in the case of settlements with the similar size to Szeged, with larger cities, the same could be more difficult. For these reasons no UGS polygons were excluded from the analyses. Three additional modelling scenarios were performed with different input datasets, producing Scenarios 2–4 (test estimates) (Table 2). These additional population estimations were compared with the Service area + HMI reference estimates to quantify the limitations of the buffer zone-based isochrone mapping methodology and Urban Atlas population data in further analyses.

2.6. Further refinement of UGS polygons and travel durations by ownership and attractiveness

Since the size of Szeged made it possible, as an additional analysis, UGS provision was also estimated with a different set of rules, in order to capture the attractiveness aspect of UGS provision as well. Firstly, each Urban Atlas polygon were manually re-evaluated, whether it represents a real public place or not. Entry points that were deemed to belong to private areas, were excluded from further analyses. The remaining polygons were evaluated by their potential attractiveness to city dwellers. This potential attractiveness was calculated by two indicators: area and the number of point of interests (POI). Since Urban Atlas polygons of various areas are often fragmented by the road network, in order to calculate these indicators, UGS polygons were submitted to a defragmentation process. Each UGS polygons that were separated by exclusively roads (with the exception of roads categorized as tertiary, secondary, primary or highway in OpenStreetMap) were merged together. Based on the National open space guidelines (Stessens et al., 2017) UGS polygons were divided into three groups by their size: pocket, local and district UGS. The number of POIs (provided by OpenStreetMap) was calculated within these defragmented polygons as well. Different maximum travel times were taken into account based on these two indicators (area and POI count) in the case of the entry points of each individual UGS polygon. The maximum travel times of each entry points were based on the National open space guidelines (converted from maximum distance with 5 km/h walking speed) and were further refined by the POI numbers. UGS polygons that contained at least 1 POI were divided into five subcategories with natural breaks method, and their standard maximum walking times were expanded by +1 to +5 min accordingly (see Table A1). With these new set of rules, the same four scenarios were carried out as in the case of Table 2.

2.7. Quantifying input data limitations in UGS provision estimation

The output of the UGS provision assessment in the four cases (reference and test estimates) was a population number series of 16 values. The first 15 values involved people living in the continuous urban fabric able to reach the nearest UGS entry point from their homes for each minute from 1–15. The sixteenth value is the number of people unable to reach any UGS entry point from their homes within 15 min (requiring >15 min). To quantify the limitations of buffer zones and the Urban Atlas population data in the UGS provision estimation (i.e. the numeric deviance of test estimates from Service area + HMI reference estimates) the following statistical analyses were conducted:

- We analysed the descriptive statistics (minimum, maximum, range, mean, average underestimation, average overestimation and standard deviation) of the estimation differences between the Service area + HMI reference estimates and the test estimates. The estimation differences for inhabitants for each walking distance area were also expressed in percent.
- Since previous studies suggest 10−15 min as optimal walking duration for UGS access (Stanners and Bourdeau, 1995; Pafi et al., 2016; Kovacs-Györi et al., 2018; Le Texier et al., 2018; Poleman, 2018), we summarised the estimated population within the 1–10 and the 1–15 min walking distances for each Output. The difference between the Service area + HMI reference estimates and test estimates were calculated and expressed in percent.
- Finally, a simple linear regression analysis was performed between the estimated Service area + HMI reference estimates and all test estimates separately. Estimated population numbers of each walking distances of the reference was used as the dependent variables (y axis), while population estimates of the test estimates were utilised as the independent variables (x axis) in the analyses. This method generates a linear function best fit the dependent and independent variables. The relationship between the variables, e.g. the correlation coefficients (r^2), P-values (p) and the residuals have the potential to show similarities in the output for various modelling scenarios. Therefore, these might provide additional information on the limitations of the buffer zone-based methodology and Urban Atlas population data in UGS provision analyses. Furthermore, the residuals (measuring the differences between the observed values of y and the predicted values of y at each value of x) of each of the 16 walking distances were calculated that gives information about how well the model fits to the observed (reference) data:

$$e = y - \hat{y}$$

where

e is the residual

y is the observed value of the independent variable (capita) in the simple linear regression analysis

$\hat{y}$ is the predicted value of the independent variable (capita) in the simple linear regression analysis

These residuals were then assigned to the reference service areas on a map in order to get further insight to the spatial differences of the Service area + HMI reference estimates and the Test estimates. The regression analyses were conducted using the Statgraphics Centurion 18 software.

3. Results

3.1. Direct quantification of spatial accuracy between the buffer zone and the service area-based isochrone maps

The generated isochrone maps delineate areas in the city with low UGS entry points including the continuous urban fabric (Fig. 3). According to the service areas (A), there are two major areas in the continuous urban fabric (one in the NW and another SSW of the area) from where the closest UGS entry point is unreachable within 10 min of walking. Although buffer zones (B) show lower walking times in these areas, the hotspots are clearly visible on the isochrone map.

The difference map, created by overlaying the two isochrone maps (Fig. A2), demonstrates that compared to service areas, buffer zones provide better accuracy in walking time estimates near the UGS entry points (the estimated walking distance difference between the two maps is zero). These areas reveal 1−3 min estimation difference, meaning that

Table 3
Descriptive statistics for the isochrone difference (t) and population difference (p) maps.

	t (min)	p (capita)
Minimum	−14.0	−672
Maximum	3.0	572
Range	17.0	1244
Mean	−3.6	13
Weighted mean	−1.5	15
Average underestimation	−5.3	−50
Weighted average underestimation	−3.4	−65
Average overestimation	1.5	57
Weighted average overestimation	1.0	69
Standard deviation	4.1	92
Weighted standard deviation	2.7	112

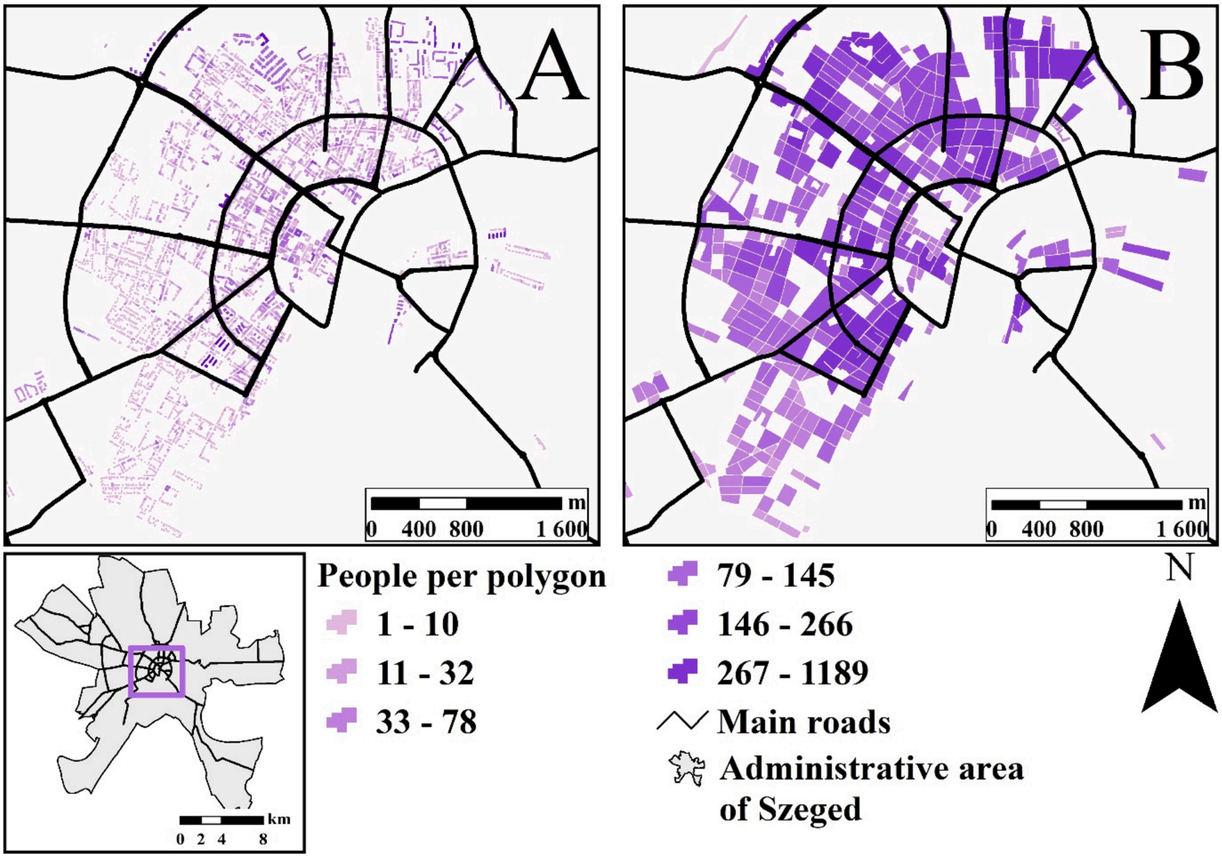

Fig. 4. Reference input for (A) the building-scale population data from the Hungarian Ministry of Interior (HMI) and (B) population data from the Urban Atlas.

the buffer zone-based isochrone map produces longer walking times to the closest UGS entry points than the service areas. Further areas of accurate estimates occur radially, but the overall tendency involves a negative estimation difference, supporting shorter walking time estimates from buffer zones.

The data involves a considerably wide (17 min) range, meaning that occasionally, the buffer zone-based isochrone map produced very different estimates compared to the service area-based map. The range however, is very sensitive to high or low outliers present in the data. The arithmetic mean and standard deviation provide more information on the spatial accuracy of the buffer zone-based isochrone mapping methodology. The average time estimation difference for the data is –3.6 min with standard deviation of 4.1 min. When weighted by the polygon size, the average time estimation difference decreases to –1.5 min with a weighted standard deviation of 2.7 min (Table 3).

3.2. Direct quantification of overall accuracy between Urban Atlas and HMI's building-scale population data

The two input population data show similar distribution in the continuous urban fabric, although the Urban Atlas data are rougher (Fig. 4). The building-scale data provides a population of 60,070 in the continuous urban fabric, whereas the Urban Atlas yielded 67,145 residents in the same area.

The difference map of the two input population layers (Fig. A3) indicates that the Urban Atlas data underestimates and overestimates population compared to the building-scale dataset, although these inaccuracies are low compared to the population in the study area. In this area, the Urban Atlas data shows higher population size in the continuous urban fabric than the HMI reference data, accounting for the population overestimation dominance. However, no spatial pattern is

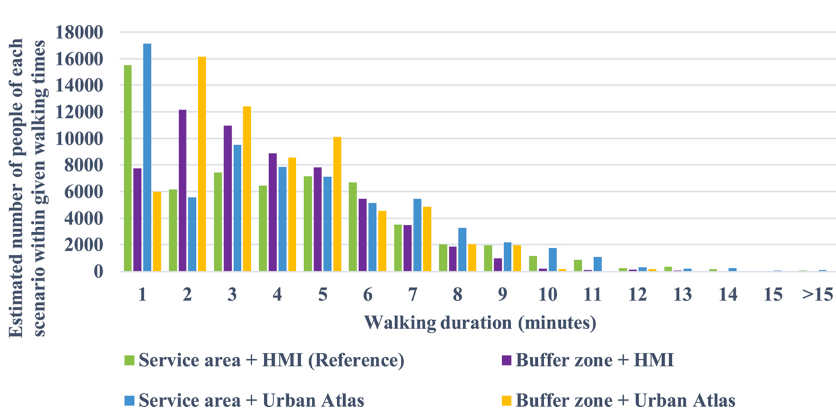

Fig. 5. Estimated populations for each scenario (reference and test estimates) within a minute's resolution of the walking duration.

Table 4
Descriptive statistics of the population estimation differences for test estimates compared to the Service area + HMI reference estimates.

Modelling scenario	Min.	Max.	Range	Av. underestimation	Av. overestimation	St. Deviation
Buffer zone + HMI test estimates	−7781	6004	13,785	−1054	3162	2735
Service area + Urban Atlas test estimates	−1560	2082	3642	−786	787	945
Buffer zone + Urban Atlas test estimates	−9552	9962	19,514	−1432	3565	3824

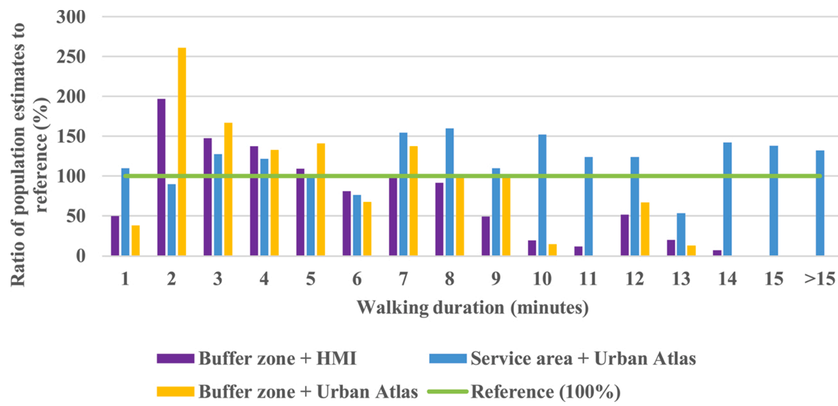

Fig. 6. Estimation differences for test estimates relative to reference estimates for various walking durations. Bars above the reference line (100 %) mean over-, while below the reference line mean underestimation.

evincible between under- and overestimated areas, with random population distribution differences between the two databases.

Contrary to differences in the isochrone maps, the population differences are within a relatively narrow range (1244 people) due to moderate minimum and maximum values. Weighting by the polygon size increased both the mean (mean = 13 people, weighted mean = 15 people) and the standard deviation (Std Dev = 92 people, weighted Std Dev = 112 people) of the estimation differences of the two data sources (Table 3).

3.3. Quantification of the spatial accuracy by the differences of the UGS provision estimation methods

The Service area + HMI reference estimates of the UGS provision assessment reveal that 26 % of residents (15,540 people) of the continuous urban fabric are within a minute of walking from the nearest UGS (Fig. 5).

The results also demonstrate that 97 % of the population (58,270 people) are within 10-minutes walking distance from a UGS entry point. The estimated population values for Buffer zone + HMI test estimates deviate only marginally from the Service area + HMI reference estimates for walking distances of 5–8 min. In the 9–15 min interval, Buffer zone + HMI test estimates underestimates the population, whereas overestimation occurs in the 2–4 min walking distance intervals. The highest estimation difference is displayed by the shortest walking distance (1 min), characterised by major underestimation. The standard deviation of the estimation differences for Buffer zone + HMI test estimates and Service area + HMI reference estimates is 2735 people, which is significant compared to the population of the continuous urban fabric areas (60,070 people). The range of values is also high (13,785 people) because of outliers in the data (high estimation differences for the 1- and 2-minutes walking distances) presented in Table 4.

Among the three test scenarios, the results for Service area + Urban Atlas test estimates provide the most accurate estimates compared to the reference results. The range (3642 people) and the standard deviation (945 people) of the estimates are the lowest among the Scenarios. The Buffer zone + Urban Atlas test estimates created the least accurate estimates compared to Service area + HMI reference estimates. The range (19,514 people) and the standard deviation (3824 people) of the

Table 5
Estimated populations within 1–10 and 1–15 min walking distances as well as within the total area (all walking distances) according to different scenarios.

Population (capita)	Service area + HMI reference estimates	Buffer zone + HMI test estimates	Service area + Urban Atlas test estimates	Buffer zone + Urban Atlas test estimates
Estimated within 10 min	58,270	59,749 (+2.5 %)	65,131 (+11.8 %)	66,933 (+14.9 %)
Estimated within 15 min	59,993	60,070 (+0.1 %)	67,043 (+11.8 %)	67,145 (+11.9 %)
Total observed population	60,070	60,070 (±0%)	67,145 (+11.8 %)	67,145 (+11.8 %)

estimation differences for Buffer zone + Urban Atlas test estimates compared to Service area + HMI reference estimates are considerable. The differences of the buffer zone-based test estimates (Buffer zone + HMI and Buffer zone + Urban Atlas test estimates) compared to the Service area + HMI reference estimates are inconsistent (in both positive and negative directions). The results for Service area + Urban Atlas test estimates, however, exhibits a more consistent overestimation of low magnitude. Fig. 6. Further emphasizes the estimation differences compared to the reference in a percentage value. Bars in the line (100 %) represents overestimation (estimate > reference), while below it represent underestimation (estimate < reference).

The estimated populations for the four scenarios within the 10−15 min walking distance as well as the populations (the >15 min walking distances included) are presented in Table 5.

Despite the high estimated population difference between individual walking distances, the total estimated population within 1–10 min walking distance for Buffer zone + HMI test estimates only differs from Service area + HMI reference estimates by 2.5 %. In the 1–15 min walking distance intervals, the difference drops to 0.1 %. For Service area + Urban Atlas test estimates, the sum of the estimated population for the 1–10 and 1–15 min walking distances deviates from the reference more than Buffer zone + HMI test estimates (11.8 % in both cases). Buffer zone + Urban Atlas test estimates produced an estimate that is 14.9 % higher within the 1–10 and 11.9 % for the 1–15 min walking

Table 6
Summary table for the results of the simple linear regression analysis, which shows the results of estimated populations of the sixteen walking durations for the reference estimates and the test estimates.

Variable	Correlation coefficient (r^2)	P-value (p)	Number of pairs
Buffer zone + HMI test estimates	0.7878	0.0003	16
Service area + Urban Atlas test estimates	0.9798	<0.0001	16
Buffer zone + Urban Atlas test estimates	0.663	0.0051	16

distance compared to Service area + HMI reference estimates. Regression analyses highlight significant statistical connections between Service area + HMI reference estimates and others, with the strongest positive significant correlation ($r^2 = 0.788$. $p < 0.0001$) between Service area + HMI reference and Service area + Urban Atlas test estimates. Meanwhile the weakest positive significant correlation ($r^2 = 0.663$, $p = 0.0051$) is between Service area + HMI reference estimates and Buffer zone + Urban Atlas test estimates (Table 6). These results are congruent with those of the descriptive statistics. Fig. A4 shows the calculated residuals of the simple linear regression analyses assigned to the reference service area polygons of the corresponding walking distances.

3.4. *The impact of attractiveness-based maximum travel time diversification on result estimates*

In the isochrone maps, where private UGS polygons were excluded and the different level of attractiveness corresponded to different maximum walking times, a large area with poor UGS provision is clearly delineated (Fig. 7). A smaller area with bad UGS provision was also observed in the northern part of Szeged.

Fig. 8. Shows that the overall pattern of the four scenario's population estimates changed only slightly compared to the main analyses where every Urban Atlas UGS polygons were treated equally regarding their maximum walking durations. The most apparent changes are the gap between the 3 and 4 min walking times and the increased number of estimated people in the 10- and 11-minutes walking times.

The over- and underestimations compared to the Service area + HMI reference estimates seem to show a slight decrease in comparison to the estimations with equal maximum travel times (Fig. 9).

4. Discussion

4.1. *Limitations of buffer zones in UGS provision estimations*

Comparing the sum of the estimated populations of the Buffer zone + HMI and Buffer zone + Urban Atlas test estimates to that of Service area + HMI reference estimates within 1–10 and 1–15 min walking distances, it was found that using the buffer zone-based isochrone mapping methodology instead of service areas produces only minor total population estimation differences (0–2.5 % compared to the reference), although these differences seem to be inconsistent (Table 5). On the other hand, however, population estimates between the 15 individual 1-minute walking distances appear to be high and inconsistent. Because the shapes and sizes of buffer zones can differ significantly from service areas, population estimates in the present methodology may highly depend on spatial inequalities of the population density. This likely explains the major estimation differences between Service area + HMI

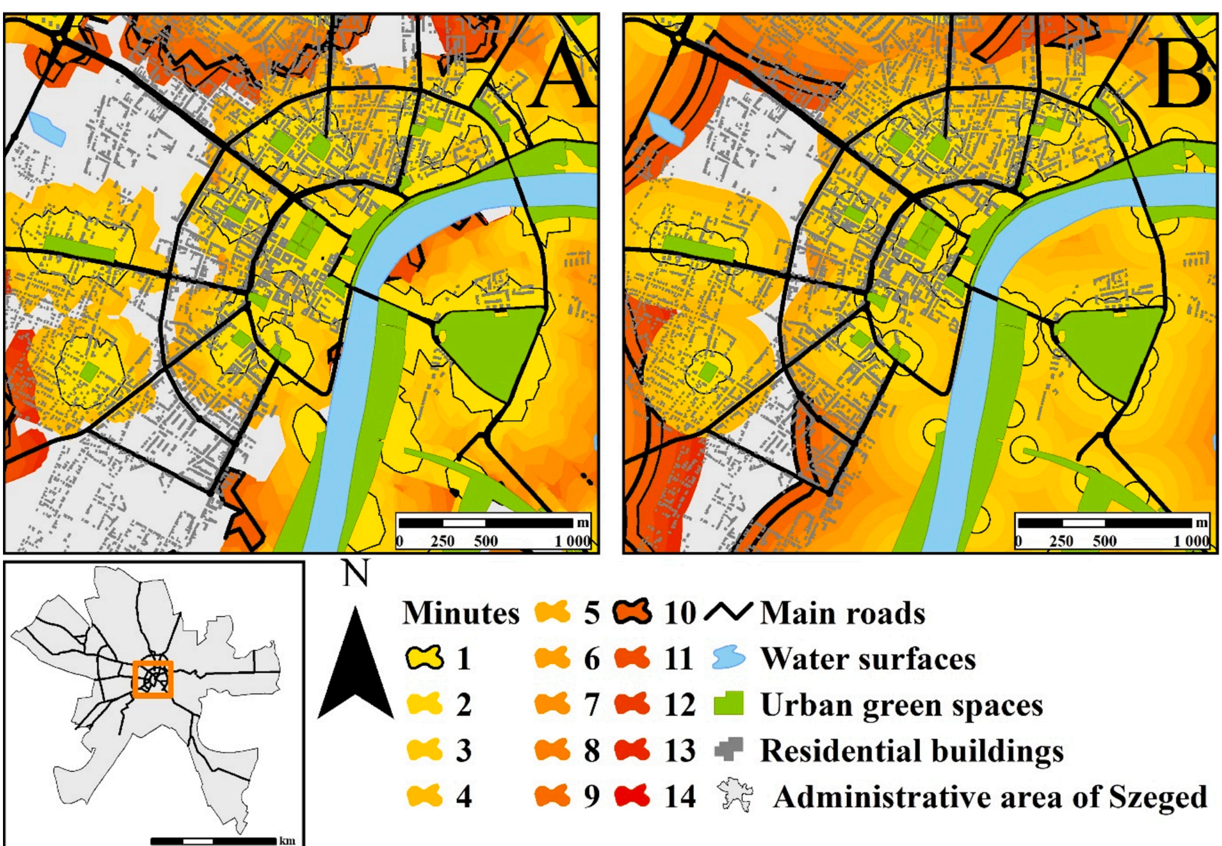

Fig. 7. Estimated walking distances in minutes according to the (A) service area and (B) buffer zone-based isochrone maps when different maximum walking distances are assigned to urban green spaces with different level of attractiveness. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

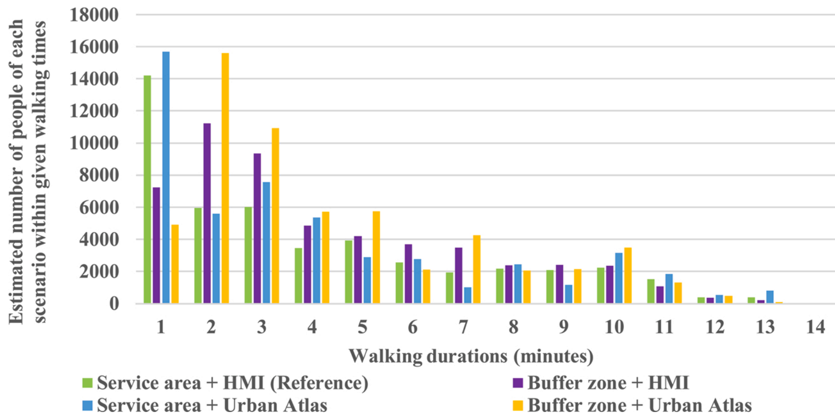

Fig. 8. Estimated populations for each scenario (reference and test estimates) within a minute's resolution of the walking duration when different maximum walking distances are assigned to urban green spaces with different level of attractiveness. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

reference estimates and Buffer zone + HMI test estimates for the 1- and 2-minutes walking distances (Figs. 5 and 6). This inconsistent spatial accuracy of the buffer zone-based results implies a reduced utility as alternative for the service area-based methodology for future studies.

Our study supports Shahid et al. (2009); Le Texier et al. (2018), and Mora-Garcia et al. (2018) that buffer zones tend to underestimate walking times between points. It was found however, that under shorter distances (1−3 min walking times) accurate travel time estimations (or slight overestimations) are also possible with buffer zones. In the case of smaller UGS, categorized by pocket or local green spaces by the National open space guidelines (or similar area-based UGS categorization methodologies) (Stessens et al., 2017), where the maximum suggested travel time seldom exceeds 3 min, buffer zone-based isochrone mapping might be a fast and effective alternative. For city-scale assessments, replacing a detailed service area-based isochrone map with buffer zone map is inadvisable. Network analysis-based methodologies (e.g. service areas) such as the work of Gu et al. (2017); Zhang and Tan (2019) or Wen et al. (2020) are better fit to UGS provision estimation analysis in the case of cities with the scale similar to Szeged. The comparison of our result isochrone maps suggest that buffer zones predicted unrealistically good travel times to the entry points during the analyses. These results coincide the findings of Koppen et al. (2014) and Gupta et al. (2016).

4.2. Limitations of Urban Atlas population data in UGS provision estimations

The Urban Atlas data produced 7075 more people than the HMI in the continuous urban fabric zones of the study area. This difference can be caused by multiple reasons such as population changes between the surveyed years and accuracy loss due to downscaling of the census data used for the Urban Atlas. Using the Urban Atlas population data instead of the building-scale HMI data involved a consistent 11.8 % estimation differences in the 1–10 and the 1−15 min intervals compared to the Service area + HMI reference estimates in the case of both the Service area + Urban Atlas and Buffer zone + Urban Atlas test estimates. This 11.8 % difference reflect the ratio of the total observed populations of the two data sources, which is also 11.8 % within the continuous urban fabric of Szeged (Table 5).

Based on the results, the overall accuracy of the Urban Atlas' population data are suitable as input data for UGS provision assessments, in case of the absence of more detailed population data. Though the pattern of Urban Atlas polygons with under- and overestimated population values compared to the reference are random, these differences are mostly minor within the study area. Through UGS provision modelling, the Urban Atlas appears as a reliable population data source. Although it overestimated the total population in the study area compared to the reference, the data exhibits appropriate accuracy for the UGS provision analyses.

Similarly to the findings of Zepp et al. (2020), both Urban Atlas LULC polygons and its population data are proven to be a useful tool for the assessment of city dwellers supply of UGS. The LULC polygons and population data of Urban Atlas, similarly to previous studies (Pazúr et al., 2017; Kovács et al., 2019; Kukulska-Kozieł et al., 2019; Quatrini et al., 2019) display versatile applicability throughout this study. The

Fig. 9. Estimation differences for test estimates relative to reference estimates for various walking durations when different maximum walking distances are assigned to urban green spaces with different level of attractiveness. Bars above the reference line (100 %) mean over-, while below the reference line mean underestimation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

results show that studies, like the work of Quatriny et al. (2019), where network analysis-based service areas, Urban Atlas LULC polygons and population data sources are equally utilised to estimate UGS provision now can use the own built in population database of the Urban Atlas with relatively good accuracy without having to rely other external population data sources. The overall inaccuracy appears predictable from the output values (consistent overestimation for various walking distances), suggesting a predictable margin of error in similar studies.

4.3. Combined effect of buffer zones and Urban Atlas population data on the UGS provision estimates

Completely replacing detailed input parameters with alternatives causes high under- and overestimations, and therefore should be

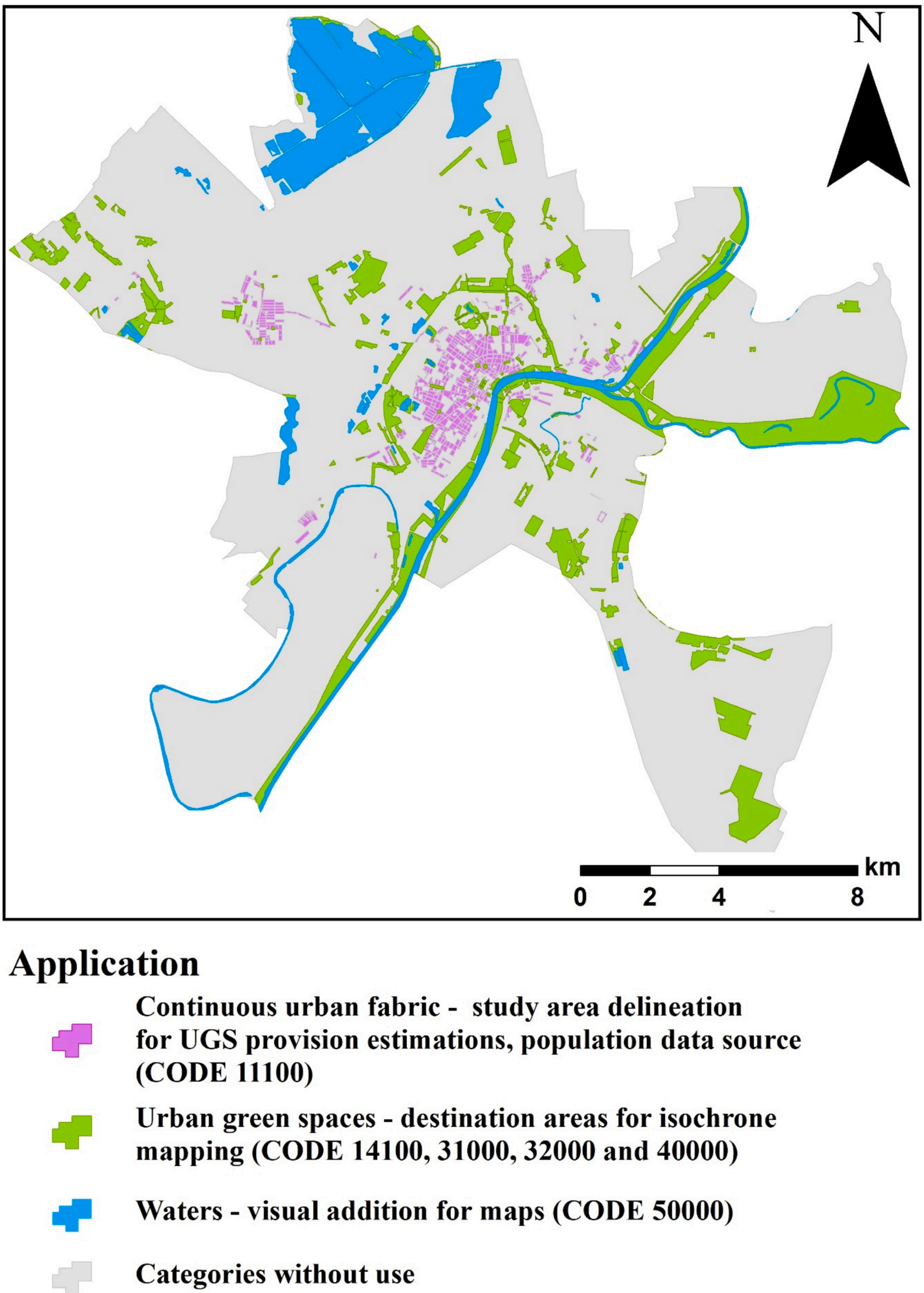

Fig. A1. Land use and land cover polygons of Urban Atlas colored by their application in this study.

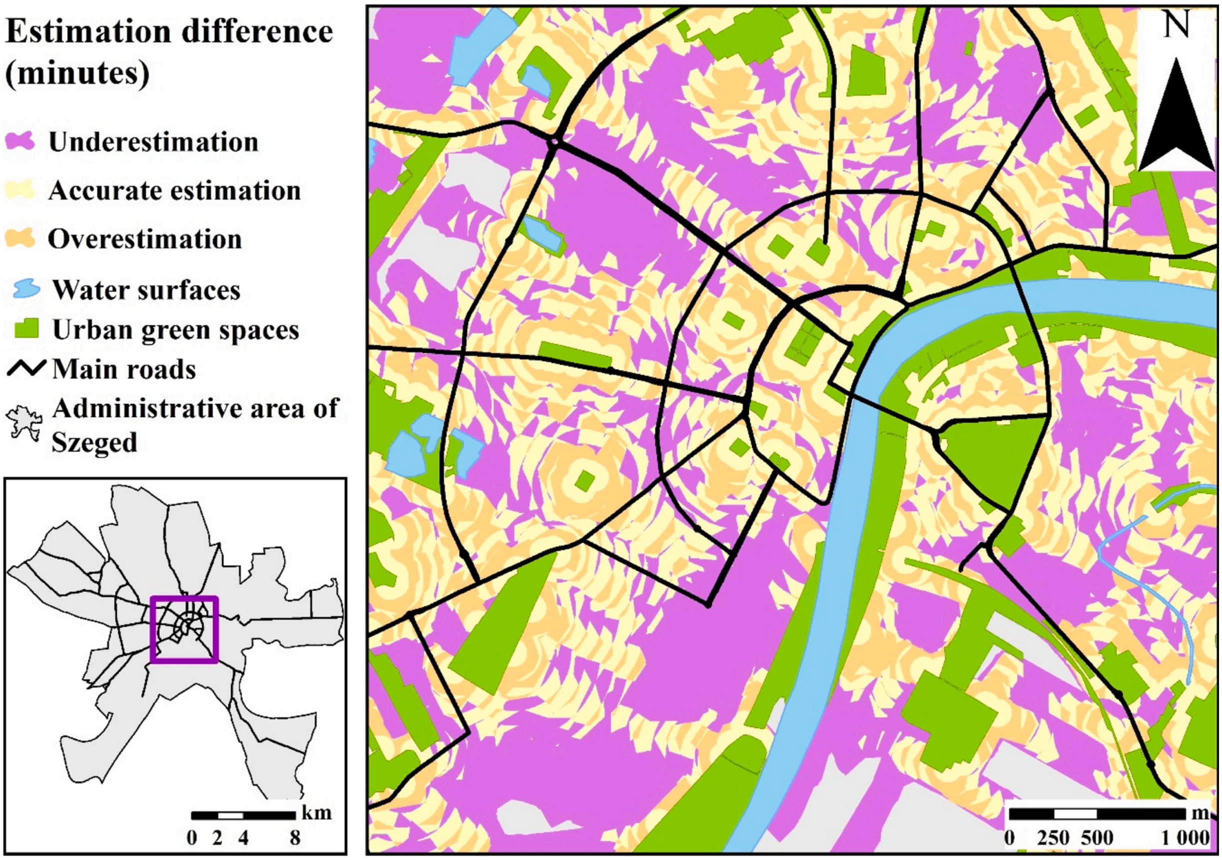

Fig. A2. Walking time estimation differences (in minutes) between the buffer zone and the service area-based isochrone maps.

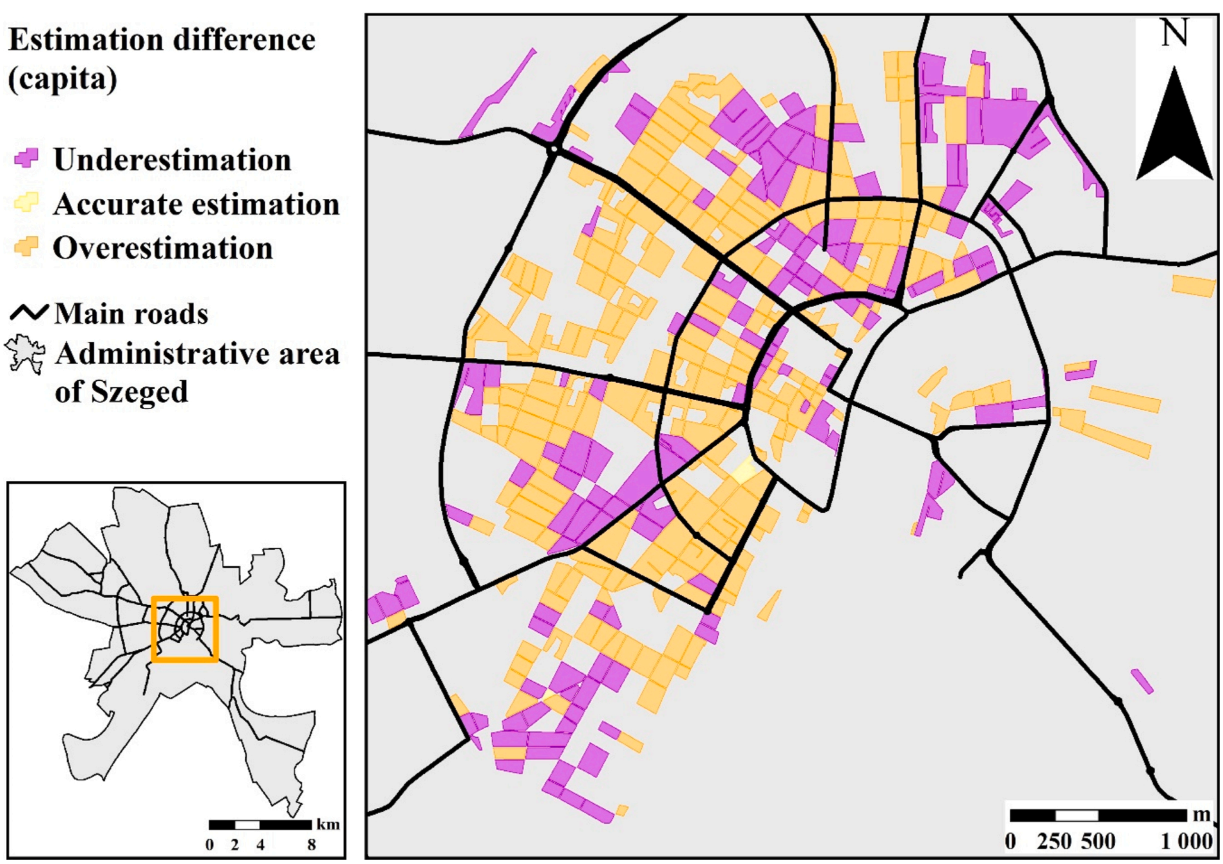

Fig. A3. Differences between the Urban Atlas population data and the reference building-scale population data (capita) in the continuous urban fabric of Szeged.

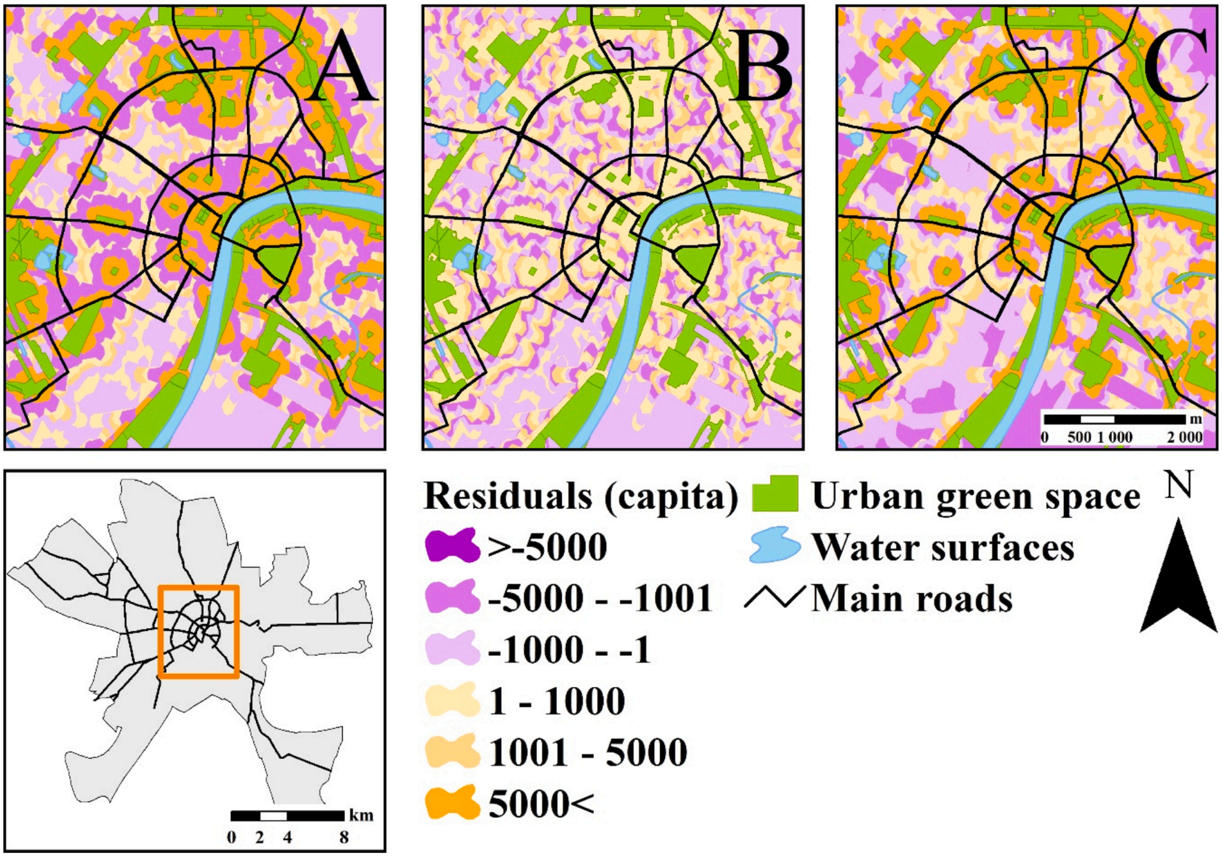

Fig. A4. The differences between the number of residents predicted by the linear function of the regression analyses and the observed number of residents (residuals) in the case of Buffer zone + HMI test estimates (A), Service area + Urban Atlas estimates (B) and Buffer zone + Urban Atlas test estimates (C). Values are depicted on the reference service area polygons.

avoided. The estimated population distribution pattern for individual walking distances (Figs. 5 and 6) show similarity for Buffer zone + HMI and Buffer zone + Urban Atlas test estimates. Since the buffer zone-based map was used instead of the service area-based map in both scenarios, we conclude that the present model is more sensitive to the isochrone map used than to the population data. This strengthens the results more on the nature of spatial as well as thematic and scale inaccuracy patterns.

Table A1
Calculated maxmum walking distances based on attractiveness (based on Stessens et al., 2017).

UGS category by area	Standard maximum walking time (rounded)	Quantity of POI within USG	Corresponding walkig time modification	Modified maximum walking time
Pocket park (0.01–0.3 ha)	1 min	0	no modification	1 min
		1–4	+1 min	2 minutes
		5–9	+2 min	3 min
		10–23	+3 min	4 min
		24–50	+4 min	5 min
		51–71	+5 min	6 min
Local park (0.3–10 ha)	2 minutes	0	no modification	2 minutes
		1–4	+1 min	3 min
		5–9	+2 min	4 min
		10–23	+3 min	5 min
		24–50	+4 min	6 min
		51–71	+5 min	7 min
District park (10–1000 ha)	10 min	0	no modification	10 min
		1–4	+1 min	11 minutes
		5–9	+2 min	12 minutes
		10–23	+3 min	13 minutes
		24–50	+4 min	14 minutes
		51–71	+5 min	15 min

5. Conclusions

In this study, the limitations of two freely accessible input databases were assessed (the buffer zone-based isochrone map and Urban Atlas LULC and population database) for spatial analyses of UGS provision. Due to the predictable inaccuracies, the Urban Atlas' population data exhibited suitability for UGS provision estimations. For our study area (Szeged), the 2012 version of the Urban Atlas overestimated the population in the continuous urban fabric areas by 7075 compared to the reference data (weighted average estimation difference/Urban Atlas polygon = 15 people). Therefore, on average, the UGS provision assessment performed, using the data, have slightly overestimated the population (consistently overestimating the local population by 11.8 % for 1–10 and 1–15 min walking distances).

The buffer zone-based isochrone maps were also useable in UGS provision estimations but to a smaller extent because walking distances are commonly underestimated in this approach. According to our results, the approach averagely predicted walking times 1.5 min lower compared with the service areas. The estimation differences were also smaller (2.5 % for the 1–10 and 0.1 % for 1–15 min walking distances). The inconsistent buffer zone- based UGS provision estimates demonstrated smaller reliability compared to the population data of the Urban Atlas. The concurrent application of the buffer zone-based isochrone map and Urban Atlas population data seemed unadvisable.

To the best of our knowledge, no previous study tested different sources of population data in UGS provision estimations. In the near future, a new Urban Atlas containing more recent information on the LULC structure and population of European cities is expected. A nonvalidated beta version is already available, but population data is not yet attached to its attribute table. An accuracy test using the new data will further highlight limitations of using the Urban Atlas' population data for UGS provision assessments. Our results improve knowledge on the utility as well as the spatial, thematic and scale accuracy of such input data in UGS provision mapping, with potential for enhancing the reliability of similar studies. Future studies should focus on similar tests of the limitations of these widely accessible input data sources in other European cities as well. We believe that such studies would further strengthen the results presented in this paper and at the same time our results could prove to be an adequate base for these future assessments.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests.

CRediT authorship contribution statement

Ronald A. Kolcsár: Conceptualization, Investigation, Methodology, Software, Writing - original draft, Writing - review & editing, Visualization, Data curation. **Nándor Csikós:** Data curation, Software, Writing - original draft, Writing - review & editing. **Péter Szilassi:** Conceptualization, Investigation, Methodology, Supervision.

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Appendix A

Abbreviations:
UGS urban green spaces
LULC land use and land cover
HMI Hungarian Ministry of Interior
POI point of interest

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